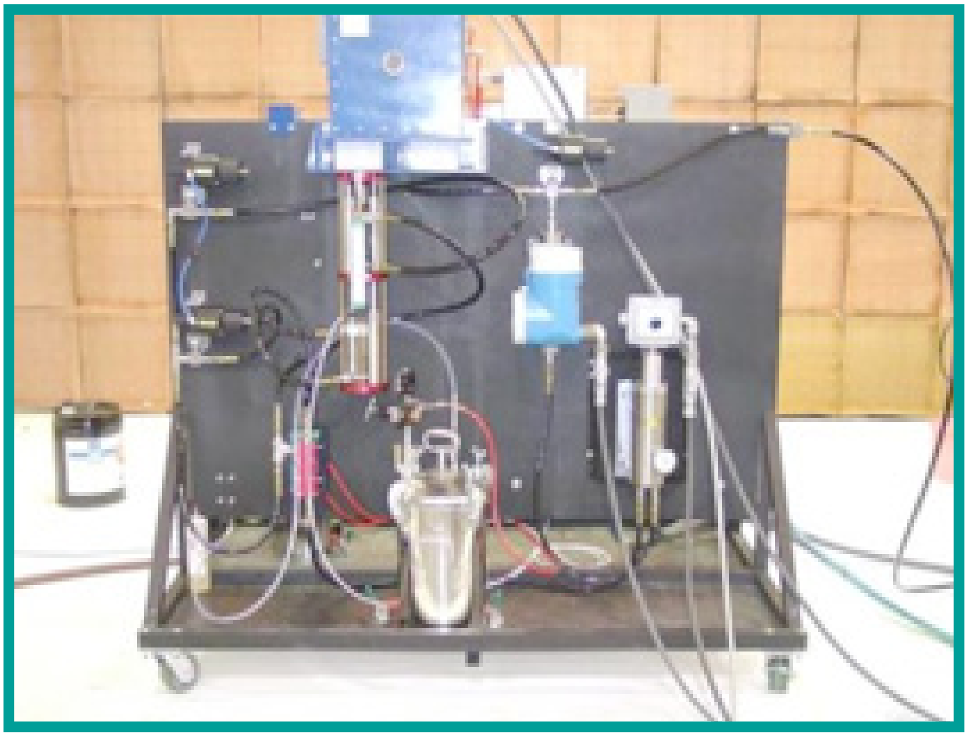
ESTCP
Cost and Performance Report

(WP-0408)



UV Curable Elastomeric Materials

January 2009

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JAN 2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**
4. TITLE AND SUBTITLE **UV Curable Elastomeric Materials**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Environmental Security Technology Certification Program (ESTCP),4800 Mark Center Drive, Suite 17D08,Alexandria,VA,22350-3605**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**82**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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ACRONYMS AND ABBREVIATIONS

CAA	Clean Air Act
DCAA	Defense Contract Audit Agency
DoD	Department of Defense
DSS	Defense Security Services
ECAM	Environmental Cost Analysis Methodology
ESTCP	Environmental Security Technology Certification Program
FMI	Foster Miller Inc.
HAP	hazardous air pollutants
HAZMAT	hazardous material
HF	Hydrofluoric Acid
IRR	Internal Rate of Return
NESHAP	National Emissions Standards for Hazardous Air Pollutants
NGC	National Guideline Clearinghouse
NPV	Net Present Value
OEM	original equipment manufacturer
P2	pollution prevention
PUVD	polyether/polyurethane oligimer
PWA	Pratt & Whitney Automation
RCRA	Resource Conservation and Recovery Act
RTO	regenerative thermal oxidizer
SAM	surface-to-air
SERDP	Strategic Environmental Research and Development
UCAV	unmanned combat air vehicle
UV	ultraviolet
VOC	volatile organic compound

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ACKNOWLEDGEMENTS

This report was prepared by Madeleine Low, Northrop Grumman Corporation, El Segundo, California, under project number WP-0408 for the Environmental Security Technology Certification Program (ESTCP).

The following organizations provided invaluable contributions to this document:

- Air Force Research Laboratory, Dayton, Ohio
- Boeing Aerospace, St. Louis, Missouri
- Environmental Security Technology Certification Program
- Foster Miller Incorporated, Waltham, Massachusetts
- Fusion UV Systems, Gaithersburg, Maryland
- Lockheed Martin, Fort Worth, Texas
- NavAIR, Patuxent River, Maryland
- Pratt and Whitney Automation, Huntsville, Alabama
- Universal Technology Corporation, Dayton, Ohio

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1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

Elastomeric coatings used for aerospace applications typically contain volatile organic compounds (VOC) and hazardous air pollutants (HAP) such as methyl ethyl ketone, methyl isobutyl ketone, toluene, or xylene at levels as high as 600 g/L. Despite this fact, these coatings are currently exempt from 1998 National Emissions Standards for Hazardous Air Pollutants (NESHAP) due to the lack of a suitable low-VOC substitute as well as their low usage volume at the time the regulation was drafted and passed. Since that time, the requirement for use in aerospace applications of these coatings has substantially increased. Over the next decade, the U.S. military plans to deploy several new weapons systems that use elastomeric coatings and technology to retrofit several existing systems, including the use of elastomeric coatings to improve the performance of the aircraft. As a result, the emission of VOC from elastomeric coatings is expected to increase to about 2 million pounds per year.

In addition to environmental issues, the process for applying elastomeric coatings is time and labor intensive due to the relatively thick coatings that are applied. The required thickness is achieved by applying multiple layers. Applying these coating to an aircraft or missile weapon system is a very cumbersome process and usually requires multiple shifts.

The objective of this program is the demonstration and validation of innovative technologies that will result in a nearly 100% reduction of VOC emissions from an elastomeric coating spray application. The coating resin used in this program was developed by Foster-Miller, Inc. (FMI) in part under Strategic Environmental Research and Development (SERDP) funding (WP-1180). This specific resin was chosen based on its potential ability to allow cure of thick layers of filled formulations. The ultraviolet (UV) coating technology has the potential to provide 90% reduction in application and cure time, thus reducing life-cycle costs tremendously and improving mission readiness of the aircraft.

1.2 OBJECTIVES OF THE DEMONSTRATION

The objective of the project demonstration was three-fold:

1. Demonstrate that the FMI UV curable resin can be tailored to meet specific weapon system requirements through the addition of appropriate fillers and additives
2. Validate that the material can be spray-applied and cured in order to demonstrate compatibility with production and field application methods
3. Demonstrate that the coating is amenable to field repair and the repaired coating maintains its aerospace performance characteristics.

1.3 REGULATORY DRIVERS

The need to reduce pollution is driven by regulatory issues and government policies. NESHAP has been the principal compliance driver over the last decade for the aerospace industry, in particular NESHAP 40 CFR Part 63. Hazardous material (HAZMAT) reduction is driven by the Clean Air Act (CAA) and Resource Conservation and Recovery Act (RCRA) through pollution prevention (P2) efforts. Many P2 projects impact both CAA and RCRA concurrently. Examples are:

- CAA: Solvent substitution replacing high vapor pressure solvents with compliant, lower vapor pressure chemicals, utilizing non-VOC and/or non-HAP solvents and coatings, powder coat applications vs. conventional coating, etc.
- RCRA: Reducing or eliminating toxic/corrosive/flammable/reactive waste streams through material substitution, increasing recycling efforts for solid waste, etc.

Both the CAA and RCRA mandate either directly or indirectly that efforts to minimize pollution be instituted. The CAA under the NESHAP 40 CFR Part 63 places restrictive limits on material use. Most Department of Defense (DoD) coatings fall under the NESHAP regulations although the coatings addressed here are exempt because of their application. However, VOC limitations are often placed on manufacturing and repair facilities based on the limits of their operating permits and can therefore restrict operations. Further, the baseline coatings typically contain large quantities of solvents that in many cases are considered to be hazardous air pollutants. The UV curable coatings eliminate solvents and HAPs thereby facilitating compliance with air quality regulations at DoD manufacturing and repair facilities.

When signing a Hazardous Waste Manifest, the generator declares that they have a program in place to reduce the volume and toxicity of waste generated to the degree determined to be economically practicable. This minimizes the present and future threat to human health and the environment. The UV curable coating technology eliminates hazardous waste by reducing toxicity and volume of paint-related waste. First, the fact that material is a single component eliminates much of the waste associated with mixing and applying the coating (eliminates pot life constraints). Second, eliminating the solvents and hazardous components (such as free diisocyanate) reduces the toxicity of the waste stream. Further, since the waste that is generated doesn’t contain solvent, it is considered to be nonflammable.

When compared to the baseline materials, the UV curable coatings offer several environmental benefits:

- Eliminate VOC, HAP, and free diisocyanates from the coatings, thereby eliminating many of the employee health and safety issues associated with conventional coatings
- Eliminate VOC, HAP, and free diisocyanates from the coatings, thereby reducing facility emissions of VOC and HAP.
- Eliminate HAPs and free diisocyanates from the coatings, thereby reducing toxicity of waste streams.
- Eliminate waste associated with material mixing and pot life, thereby reducing the quantity of waste generated.

1.4 STAKEHOLDER/END-USER ISSUES

The demonstration will validate the feasibility of using UV curable materials in aircraft design as well as demonstrate the repairability of the coating. However, because of the current constraints associated with large-scale application of the coatings, many of the stakeholder issues cannot be addressed at this time (note that the application and cure equipment scale-up was identified as an option task in the original proposal). Due to the complexity of developing an elastomeric coating, the demonstration will be directed toward a specific platform with potential transitions to multiple platforms.

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2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

UV curable coatings are a new technology for the aerospace industry, and recent advances in photoinitiators and light sources have enabled the cure of both thick and filled coatings, thereby thrusting UV coatings to a heightened level of practicality. FMI has adapted this new technology and has demonstrated that a vinyl dioxolane terminated polyether/polyurethane oligimer (PUVD) combined with a variety of fillers can be cured at thicknesses of 1-4 mils (depending on the filler used) with UV irradiation in less than 30 sec with negligible change in thickness, thus resulting in significant reduction of time per pass compared to the conventional solvent-borne systems. The fillers along with the required proportions used in the SERDP program were supplied by the Boeing Company. FMI has also shown the ability of these filled PUVD layers to be applied one at a time to build up the required thickness levels (30–100 mils) for specific applications. The resulting coatings showed excellent interlayer adhesion. The proposed technology offers the following significant advantages over the current coatings used for signature management:

- Minimal shrinkage in the "as applied" wet film results in improved dimensional control.
- Cure time per pass is reduced from 15 min to 30 sec.
- VOCs, HAPs and free diisocyanates are eliminated.
- The coating can be supplied as a one-component system, thus eliminating time and error associated with mixing as well as minimizing the waste associated with unused material.

FMI's coating was demonstrated on a laboratory scale and has considerable promise for transition to several weapon systems. The current program will provide a means of carrying the technology to the next stage through process scale-up and will provide an understanding of the performance aspects of the coating in field applications. As a result, we anticipate building an awareness of the technology in the aerospace community to ease transition to various platforms for all branches of DoD.

2.2 PROCESS DESCRIPTION

UV curable coatings require two things for applications:

1. Application equipment
2. Curing equipment.

For this application, FMI's UV curable material was applied using two different techniques. The first technique used robotic spray application equipment. Many coatings are now being robotically spray-applied to the specific aircraft parts. For this demonstration of this application, a standard robotic spray system was modified to allow for the spray application of the UV curable material. Due to the high viscosity of the material, the material must be heated for spray applications. Therefore, the robotic fluid delivery system was modified to include heated fluid lines and a heated material pot. The heated fluid delivery system is shown in Figure 1.

Typical aerospace coatings are multi-part kits, (base and catalyst are in separate containers); however, the UV curable material is a single component material kit, with no additional catalyst required, therefore, the fluid delivery system was further modified for a single component application.

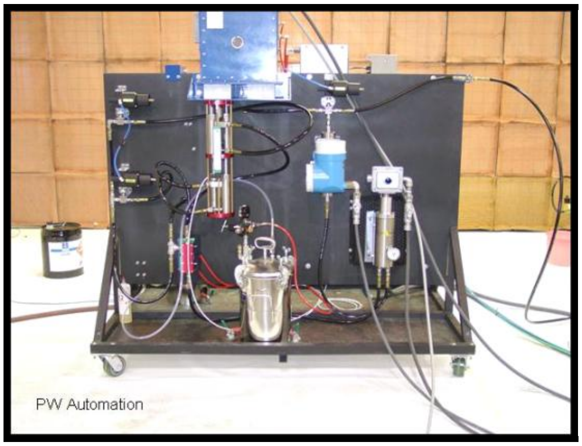

Figure 1. Single Component, Heated Fluid Delivery System.

The second application technique used to demonstrate the UV curable material was a hand repair method. For the repairs, the material would be put in the repair area, and smoothed to the desired thickness using specific tooling. After the material was applied to the desired thickness, the repair panel was cured and the next layer of material was applied using the same technique. For this method, multiple drawdown blades were fabricated with various standoff distances from the surface to control material application thickness. The tooling and equipment used for this method is shown in Figure 2.

Figure 2. Repair Tools.

To cure the UV curable materials, two cure apparatuses were used. The first apparatus was a floor-standing conveyor belt cure system, shown in Figure 3. This system was developed for laboratory curing of test coupons. It is capable of curing specimens up to 24-in-wide and the height of the lamps is adjustable for up to 6-in high. Also, the conveyor belt speed is variable based on the required exposure time to the UV light. The conveyor is equipped to cure using two types of curing bulbs in series. The system used air flow to provide cooling during the cure process.

Figure 3. Floor-Standing Conveyor UV Curing System.

The second cure apparatus used was a robotically mounted UV lamp system. This system was designed specifically for this demonstration to enable cure of a large-scale part. The mounted UV cure lamp is shown in Figure 4. This system has the capability of using one UV curing lamp at a time. The UV lamp stand-off and speed were controlled by the robotic control system. Since the robotic system was located in an open spray booth, a UV shielding curtain was installed around the spray booth to protect both the operators and the observers from exposure to high levels of UV irradiation.

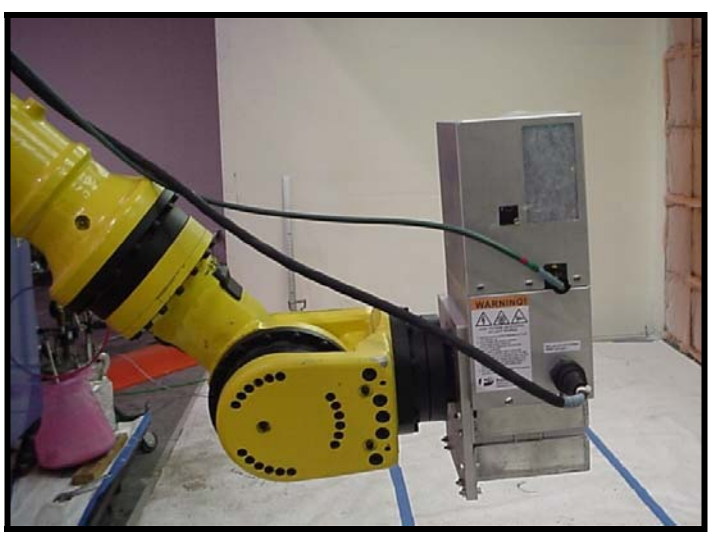

Figure 4. Robotically Mounted UV Curing System.

The application and cure equipment described above was used to apply the UV curable coating to various substrates. These substrates were then tested per various military standards described in the Demonstration Validation Plan.

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

Significant prior testing of the UV curable coating occurred under the SERDP Project WP-1181 by Foster Miller. The SERDP WP-1181 project was a 4-year effort started in FY 2001 and concluded in FY 2005. The material development and testing was performed by Foster Miller in Waltham, Massachusetts, and the material testing was performed at both Foster Miller and Boeing Phantom Works in St. Louis, Missouri. The testing protocol and the results of the testing can be found in the Final Report for the SERDP WP-1181 project found on the SERDP website.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The FMI UV curable coating developed has numerous benefits when compared to the baseline coating, including elimination of VOC emissions and hazardous waste and reduction of cycle time, labor, and capital assets.

Baseline Material and Process – The baseline coating is a multicomponent, polyurea resin with solvents and fillers, with a VOC of approximately 432 g/L. Current spray operations at Site 4, Plant 42, have a robotic spray system for applying the baseline material. The current material requires approximately 22 hours of application time per shipset. This time is predicated by several factors including material application thickness per pass, coating shrinkage due to solvent evaporation, coating dwell between coating layers, and travel time for the application robot to apply the coatings. There is also a 5-day dwell between the material application and the primer coating application to allow for solvent flash.

VOC Elimination – FMI's UV curable coating is a single component system that contains only a small amount of reactive diluents for viscosity reduction. Reactive diluents are not emitted during spraying but rather become part of the polymer upon cure. This results in a zero VOC coating. This eliminates over 1.7 million lbs of VOC emissions for the current projected order of aircraft. With a potential equivalent quantity of projected foreign military sale aircraft, the total VOC reduction will be over 3 million lbs of VOC emissions. Since zero VOC coatings are also exempt from all the environmental reporting and tracking requirements, that will reduce labor costs.

Hazardous Waste Elimination – The coating does not cure without intense UV irradiation. This will result in not requiring that the spray systems be purged and flushed with solvent between work shifts or between plane spray operations. This should have a major impact on the amount of hazardous waste associated with solvent flushing of the baseline coating, which cures within a few hours after mixing. The materials used for the coating have Draize values less the 1.8 and the fillers in the UV curable coating are nonhazardous, thus the coating does not require any additional special handling. UV curable coating waste can be cured and the waste will contain no unreacted solvent so the material can be disposed of as nonhazardous waste.

Cycle Time Reduction – FMI has developed a UV curable coating that can significantly reduce the long application and cure cycle time while meeting stringent property requirements for aerospace applications. It is anticipated that the UV curable coating and UV cure process will significantly reduce the 22-hr application cycle time and 5-day curing cycle time for coating the specific application. The UV curable material can be applied at coating thickness ranging from 10-20 mils per pass, and there is no shrinkage as the coating is 100% solids (no VOC) with minimal reactive diluents. The coating is fully reacted upon irradiation, so there is no dwell time required between passes. The only unknowns currently are the changes to the robot path planning to accommodate the new coating and the time and mode for the irradiation process.

The new spray process is capable of building an average of 15 mils dry per coating layer, while eliminating the 10-min dwell between layers. There are three additional advantages to cycle time reduction associated with the rapid cure nature of UV coatings. Instantly after coating cure you can perform thickness measurements and begin sanding. It also eliminates the 5-day dwell for solvent flash before applying the primer and topcoat.

Capital and Recurring Labor Savings – These factors will significantly impact the cycle time and work flow processes, which will minimize the number of spray booths, sanding booths, and cure areas at full-rate production levels. In fact, the UV cured material application should be able to be performed in a non-VOC controlled spray area if facilities can accommodate such an arrangement. Recurring labor will be significantly reduced as a result of the higher build rate, reduced environmental reporting requirements, and elimination of the need to mix the coating (one component). Further, the infinite pot life of the UV curable coating will potentially eliminate the need to solvent flush the system between coating operations. These solvent flushes are currently being used to ensure that material does not build up in the fluid lines and when the material has passed its pot life.

Other Reduced HAP/VOC Aerospace Elastomeric Coatings Efforts – There are multiple programs targeting the reduction of HAP and VOC emissions in various aerospace application, including the ESTCP project WP-0303. The WP-0303 effort is targeted at decreasing labor hours, reducing production and maintenance cycle times, reducing VOC emissions by 75% and mitigating material usage and waste generation. Though the WP-0303 effort's target is to reduce the VOC emissions, the UV curable materials effort will eliminate VOC emissions completely. Also, the WP-0303 program is evaluating materials that that utilize the same cure mechanism as the current material, while the UV curable materials program is looking at utilizing UV curable materials, thus has a potential for a greater reduction in production cycle time. More information on the WP-0303 project can be found on the ESTCP website.

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3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

There objectives of the technology demonstration are 1) demonstrate that the UV curable resin can be tailored to meet specific weapon system requirements through the addition of appropriate fillers, 2) validate that the material can be spray-applied and cured in order to demonstrate compatibility with production and field application methods, and 3) demonstrate that the filled material is appropriate for field use by showing that the material can be repaired and maintain its aerospace performance characteristics. The performance objectives and actual performance for this project can be found in Table 1.

Table 1. Performance Objectives.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance
Quantitative	1. Reduce VOC	98% reduction	Pass
	2. Cure time	30 sec/pass	Pass
	3. Specific gravity*	Requirement defined in Final Report	Pass
	4. Ultimate tensile strength	Requirement defined in Final Report	Pass
	5. Elongation @ break	Requirement defined in Final Report	Pass
	6. Flatwise tension	Requirement defined in Final Report	Pass
	7. Flexibility	Requirement defined in Final Report	Pass
	8. Intracoat adhesion	Requirement defined in Final Report	Pass
	9. Chemical resistance	Requirement defined in Final Report	Pass
	10. Heat resistance	Requirement defined in Final Report	Pass
	11. Salt fog	Requirement defined in Final Report	Pass
	12. Humidity resistance	Requirement defined in Final Report	Pass
	13. Fluid resistance	Meets adhesion and flexibility requirement defined in Appendix B following exposure to:	
		MIL-PRF-87252	Pass
		MIL-DTL-83133	Pass flexibility Fail adhesion
		DIL-PRF-83282	Pass
		MIL-PRF-23699	Pass
		ASM 1424 TYPE 1	Pass
		AMS 1435	Pass
		DOD-L-85734	Pass
		MIL-PRF-85570	Pass flexibility Fail adhesion by less than 10%
		DI water	Pass
	14. Time to Full Cure	Requirement defined in Appendix B	Pass
	15. Compatibility	Compatible with baseline material	Fail adhesion by less than 25%
	16. Platform performance*	Requirement defined in Appendix B	Pass
Qualitative	1. Less complex repair application	Time to apply and cure	Pass

* NOTE: This information is considered Northrop Grumman/Platform proprietary and is not available for distribution.

A detailed discussion of the actual performance of the UV curable material can be found in Section 6.2.

3.2 SELECTING TEST PLATFORMS/FACILITIES

During the first phase of the contract, several platforms were considered for application of FMI's UV curable coating technology. Ultimately, a specific platform was selected as the target platform because of its specific requirements surrounding the application of an elastomeric coating. The elastomeric coating is applied as multiple layers to obtain a final coating thickness that is thicker than typical coatings, such as primers and topcoats. Currently, the application and cure of the baseline material is driving the aircraft production schedule. By tailoring FMI's UV curable coating to this application, the cycle time associated with the coatings application can be substantially reduced. Northrop Grumman is currently working (under separate contract) with FMI, Pratt & Whitney Automation (PWA) and Fusion to scale up the robotic application and cure equipment. Currently, the majority of the resources required for the demonstration (spray and cure equipment) are located at PWA. The demonstration will be conducted in two phases and the responsibilities will be split between the companies.

- FMI will provide the raw material for the demonstration and provide technical personnel to assist with spraying and curing the coating.
- PWA will provide the spray equipment and technical support personnel to operate the spray and cure equipment.
- Northrop Grumman will provide the conveyor cure equipment (currently located at PWA), substrates to which the UV curable coating will be applied, and technical personnel to support the application and cure of the UV curable coating to the substrates. Northrop Grumman will be responsible for defining the test coupon configurations.
- Fusion will provide the portable cure equipment and technical personnel to support the cure of the UV curable coating to the substrates.

3.3 TEST PLATFORM/FACILITIES HISTORY/CHARACTERISTICS

The facility chosen for the demonstration and validation is PWA in Huntsville, Alabama (formerly CTA). This division of Pratt & Whitney's Advanced Systems Technology Inc. is a world-class robotic system integrator specializing in precision coating, coating removal, robotic manufacturing, material handling systems, and turnkey industrial robotic systems. PWA is an industry leader with the ability and expertise to customize processes and systems. As the industry leader in automation of weapon system manufacturing processes, PWA has provided robotic systems for manufacturing ground vehicles, surface-to-air (SAM) missile systems and munitions. The facility is Defense Security Services (DSS) and Defense Contract Audit Agency (DCAA) approved.

PWA provides engineering, design, validation, installation, training, and maintenance of automated manufacturing technology for an entire manufacturing facility or for a single coating or coating removal system. PWA technical and engineering personnel have a long history of successfully integrating automated systems into new or existing manufacturing environments. PWA provides conveyors, robots and reciprocators, coating or coating removal equipment, spray booths, cure ovens, part fixtures, and computer controls and has brought its experience in automated system integration to the production coating of unmanned combat air vehicles (UCAV), missiles, munitions, space vehicles and F-22, F-18, F-35 and B-2 coating applications.

3.4 PHYSICAL SETUP AND OPERATIONS

The spray and repair using FMI's UV curable material was demonstrated on December 5-6, 2006, at PWA. Following the demonstrations, test coupons were sent to National Guidance Clearinghouse (NGC) for material performance testing to validate the demonstration objectives. Testing was completed on March 16, 2007. The robotic application and conveyor system cure system were designed for application onto the test panels at approximately 20 mils per pass. The robotic application system had a heated material pot, heated fluid lines, and a heated pump. Unlike the baseline material, the UV curable material must be heated to reduce the viscosity of the material for spray application. For a large-scale test coupon, the UV lamp was set up to be mounted onto the robot system. This allowed for horizontal movement of the robot, which allowed for a large-scale test panel to be cured with the existing UV lamp system.

3.5 SAMPLING/MONITORING PROCEDURES

The robotic applications and cure procedures are outlined in the Demonstration and Validation Plan for this effort. The test coupons fabrication and testing performed for the validation are also defined in the Demonstration and Validation Plan. Please refer to that document for specific procedures and processes.

3.6 ANALYTICAL PROCEDURES

The data collected during the demonstration and validations was compared to the baseline material properties of the current material used in this application to verify that the material meets the platform requirements. The specific platform has provided input as to the acceptability of the material performance, and a pass/fail result is reported in this report.

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4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE DATA

Table 1 summarized the results of the validation testing. The validation testing shows that FMI's UV curable material meets or exceeds most requirements set forth for the material. The full test results and data were provided to the specific platform for analysis and approval. Additional discussion of the UV curable material performance can be found in Section 6.2.

4.2 PERFORMANCE CRITERIA

See Table 2 for Performance Criteria.

Table 2. Actual Performance and Performance Confirmation Methods.

Performance Criteria	Expected Performance Metric	Performance Confirmation Method	Actual Performance
PRIMARY CRITERIA (Performance Objectives) (Quantitative)			
Product testing	*Pass the testing defined in Final Report*	*Test method defined in Final Report.*	**Pass majority of requirements**
Hazardous materials -VOC emission reduced - Generated	*No hazardous waste is introduced by this technology.* *Non generated*	*VOC test method defined in Final Report.*	**Pass**
Process waste	*No process waste is introduced by this technology.*	*Operating experience*	**Pass**
Factors affecting technology performance	*Spray application and cure process will provide specimens without porosity or layering and with acceptable surface finish.*	*Cross-section analysis of the sprayed coating.*	**Pass**
SECONDARY PERFORMANCE CRITERIA (Qualitative)			
Ease of use	*Robotic operator will be trained for use of equipment.*	*Operating experience*	**Pass**
Reliability	*Robotic material application will not be affected by equipment.*	*Operating experience*	**Pass**
Versatility	*Robotic material applications will be performed on small test coupons.*	*Operating experience/Assessments*	**Pass**
Maintenance	*Setup, operating, and breakdown procedures can be designed for easy operation.*	*Operating experience/Assessments*	**Pass**
Scale-up constraints	*Scale-up will be evaluated on the effort summarized in Appendix A.*	*Operating experience/Assessments*	**Pass**

The Data Assurance/Quality Control Plan for the demonstration can be found in Appendix D.

4.3 DATA ANALYSIS, INTERPRETATION, AND EVALUATION

The data collected during the demonstration and validation was compared to the baseline material properties of the current material used in this application to verify that the material meets the platform requirements. The specific platform has provided input as to the acceptability of the material performance, and a pass/fail result is reported in this report.

4.4 TECHNOLOGY COMPARISON

The technical performance of FMI's UV curable material is summarized in Table 2 and the Final Report. Based on these results, the FMI UV curable material has equivalent or better technical performance when compared to the baseline coating for most of the material requirements. The requirements that were not met in this demonstration are discussed in Section 6.2. The greatest difference between the two coatings comes when looking at the environmental and cost drivers. Based on the analysis presented in this report, there are both environmental and cost advantages in using the FMI UV curable coating.

There are other programs targeting the reductions of HAP and VOC emissions in aerospace coatings, including the ESTCP project WP-0303. The WP-0303 effort is targeted at decreasing labor hours, reducing production and maintenance cycle times, reducing VOC emissions by 75%, and mitigating material usage and waste generation. Though the WP-0303 projects effort target is to reduce the VOC emissions, the UV curable aerospace materials effort will eliminate VOC emissions completely. While the WP-0303 program evaluates materials that utilize the same cure mechanism as the baseline material, the UV curable program evaluates materials that utilize a UV cure mechanism and has a potential for a greater reduction in cycle time. More information on the WP-0303 project can be found on the ESTCP website.

5.0 COST ASSESSMENT

5.1 COST REPORTING

The Environmental Cost Analysis Methodology (ECAM) tool is designed to facilitate the gathering and analysis of economic data in a manner that allows for more accurate evaluation of investment—especially when used for pollution prevention technologies. Typical cost analysis efforts often overlook significant costs, especially environmental costs.

For this effort, the application, cure equipment, and process are being developed under the effort summarized in Appendix A of the Final Report; therefore the full ECAM analysis cannot be completed at this time. The cost analysis will use the available data and estimates required to perform a cost analysis based on ECAM. This information will be used to provide information for the cost factors described in the Final Report, Section 2.3.

5.2 COST ANALYSIS

This cost analysis is based on the replacement of the baseline material and material application equipment with the UV curable material, application, and cure equipment. All costs are based on estimates and approximations made using the current knowledge of the current and proposed application processes.

All cost and rates are estimates and are used for planning purposes only. All cost figures are based on the cost to the performing company. All estimated cost values are based on calendar year 2007 dollars.

5.2.1 Cost Drivers

For the analysis of this technology, the cost drivers included the following: capital cost, material usage, utility usage, labor usage, facility usage, equipment maintenance, hazardous waste disposal, recurring environmental compliance costs, and the effect of cycle time on other phases of production.

5.2.2 Cost Basis

For the cost assessment, the UV curable coating is assumed to replace the baseline coating that is applied at the Northrop Grumman assembly line at Air Force Plant 42, Palmdale. The cost data was obtained from a survey of the transition to production effort that was undertaken for the baseline material and from data accumulated throughout the demonstration and validation of the UV curable coating.

Northrop Grumman is currently planning to build a facility in Palmdale capable of applying coatings at the expected high-volume production rate. Consequently, baseline operation and capital costs for full-rate production are estimated, and both must be considered in this cost analysis. The estimates for the full-rate production costs were obtained from a study by Comau Pico, a Detroit-based automotive systems integrator. Comau Pico produces the most advanced automotive assembly lines in the world. Comau Pico performed the following tasks to determine the lowest cost for the baseline coating process:

- Define ground rules and assumptions
- Develop facility layouts for proposed manufacturing sites
- Throughput simulation and analysis for proposed manufacturing plans
- Tooling assessments, recommendations, and impacts
- Equipment listing
- Time phased booth implementation based on production schedule
- Cost assessment—budget schedules and recommendations with assumptions for capital equipment, facility upgrades, and recurring costs
- Risk assessments and capital resource mitigation
- Down select of booth infrastructure concepts, manufacturing plans, and costs
- Specifications for accepted concepts.

Included in the capital and recurring cost associated with adding the full-rate production capability is the addition of multiple robotic spray booths. For each of the spray booths, the appropriate environmental filtration systems need to be installed. For this application, carbon adsorption filters and regenerative thermal oxidizers (RTO) will be required in the spray booths to prevent emission of VOCs into the atmosphere.

At the facility multiple coatings will be applied in each spray booth, including the baseline material for which the UV curable material is being evaluated as a replacement. One of the coatings that will be robotically sprayed contains Oxsol® 100 (PCBTF) in the formulation. Based on chemical analysis, the Oxsol® in the material will react with the RTO and produce Hydrofluoric Acid (HF), which is a hazardous acid and will erode the RTO with time. Therefore, carbon adsorption filters must be added to the system to mitigate the problem. The carbon adsorption filters will react with the Oxsol® prior to entering into the RTO, thereby eliminating the production of HF.

Though the carbon adsorption filters will eliminate the HF byproducts, the carbon adsorption filters preferentially absorb acetone. There is a high level of acetone in the current baseline coating formulation (the coating that the UV curable material is targeting to replace). The preferential adsorption of the acetone would increase the frequency with which the carbon adsorption filters must be changed. Two configurations have been evaluated to address the environmental filtration systems:

- **Option 1 –** Equip all spray booths with both RTO and carbon adsorption, and maintain the capability to spray the all material in every booth.
- **Option 2 –** Spray the materials containing Oxsol® and acetone in separate booths.

With the current materials, Option 1 may increase the frequency with which the filters must be changed, and Option 2 has the potential to decrease the frequency with which the filters must be changed but may increase the number of booths required. Currently, the baseline plan is to implement Option 2. This would restrict the use of booths to the specific material that is designed into the environmental filtration system, and may increase the number of spray booths needed to meet the full-rate production needs. With this potential increase in spray booths, there will be an associated increase in capital cost.

The UV curable material is developed to replace the material containing acetone. With the implementation of the UV curable coating, the acetone adsorption by the carbon adsorption filters would no longer be an issue. This could potentially reduce the number of spray booths by eliminating the need for material-specific booths, which potentially reduces the total number of spray booths needed, reducing capital and operating costs. The full benefits of using the UV curable alternative cannot be fully defined without further investigation by the EPA to determine the full filtration system required for this coating.

Since the UV curable replacement material is a zero VOC coating, the implementation of the UV curable replacement has the potential to reduce the capital and recurring cost of the environmental filtration system since there would be large a reduction of VOCs to be treated. This cost analysis will assume that the UV curable coating system will eliminate the need to spray materials containing Oxsol® and acetone in separate booths since the UV curable material does not contain acetone. Thus, UV curable equipment will be available in all booths for the purposes of cost planning in this report.

There are also potential reductions in operating and capital costs due to the time required to apply the coating. The baseline coating is applied at 2-3 mils per pass. The full application time of the baseline coating is approximately 22 hours with a required 5-day cure time prior to overcoat. The UV curable coating system can be applied at roughly 20 mils per pass, 10 times greater then the baseline coating. Also, the UV curable coating cures during the application process, therefore reducing the overall spray and cure time needed to apply this coating to an estimated 13 hours. Based on this initial evaluation of the UV cure application and cure times required, there is an estimated 90% savings in total application and cure time as compared to the baseline process. This potential reduction in cycle time manifests itself as a potential reduction of labor and energy costs as well as a potential reduction in the number of booths required, which also could further reduce both operating costs and capital costs. For this cost analysis, estimates are used for labor and energy costs. All cost estimates are for planning purposes only.

Currently the Northrop Grumman facility is planning to build and install multiple robotic spray booths. This will be done in phases, with one cell (two spray booths) being installed at each phase. The cost associated with a cell is much greater than that of a single booth; therefore, the capital and maintenance cost of each booth depends on whether one or two booths are being installed. Installation of a single booth cell is less expensive than that of a double booth cell, but the ratio of costs is not 1:2.

Estimates of the annual recurring operational costs delta of the UV curable coating from the baseline systems are shown in Table 3. All cost and rates are estimates and are used for planning purposes only. All cost figures are based on the cost to the performing company. All estimated cost values are based on calendar year 2007 dollars.

Table 3. Estimated Delta Annual Operational Cost of the UV Curable Coating from the Baseline.

Estimated Annual Usage for the Delta Cost of UV Curable Coating from Baseline Operation	
	Annual Estimated Delta of UV Curable Coating from Baseline
Material usage	$2,193,000
Utility usage	
Electricity	$62,000
Environmental costs	
Hazardous waste disposal fee	$4,208
Hardware and filters	$50,000
Other operation costs	
Labor hours	$2,754,000
Paint booth maintenance	$100,000
Total	**$5,163,208**

The following assumptions were used in evaluating the potential annual usage and costs of the two coating operations:

- All cost values are based calendar year 2007 dollars.
- All cost figures are based on cost to performing company.
- Aircraft production is assumed to be 255 planes annually.
- Estimated costs of gloves, safety glasses, and bunny suit consumption for the UV curable and baseline process are assumed to be equivalent.
- Environmental, operation, utility, and maintenance costs for the baseline and the UV curable processes are estimated as $5.50/gal of hazardous waste disposal.
- One gal of UV curable material sprays to the same thickness as approximately 2.5 gal of baseline material due to the absence of solvents. Material cost is based on estimated rough order of magnitude cost from the respective suppliers.
- An estimated 3 gal of the baseline material is flushed out due to premature curing in spray gun. This is considered in material usage and hazardous waste disposal fees.
- The baseline process is estimated to require one additional booth as compared to the UV curable material process. Booth savings is based on reduction in cycle time with the UV curable material application.
- Hardware and filter replacement costs are estimated at approximately $50,000 per year per booth.
- Electricity cost is estimated at $62,000 per spray booth per year.

- Actual labor rates are Northrop Grumman proprietary; therefore, a notional $200/hr will be used for this cost analysis.
- The space occupied by parts during heat curing, sanding, and parking is less for the UV curable system, but the associated costs cannot be estimated.

5.3 COST COMPARISON

The cost basis information was used to compare the baseline inlet duct coating system with the UV curable inlet duct coating system. The estimated cost difference between the baseline system and the proposed UV curable system is provided in Table 4. All cost and rates are estimates and are used for planning purposes only. All cost figures are based on the cost to the performing company. All estimated cost values are based on calendar year 2007 dollars.

Table 4. Estimated Delta Cost of Process Costs.

	Delta UV Curable Cost from Baseline
Initial Investment	**-$9,832,000**
Equipment design	-$2,367,000
Robotic spray system purchase	-$6,820,000
UV lamp purchase	-$90,000
Equipment integration	-$3,455,000
Spray booth construction	$3,100,000
Demonstration and Validation	-$200,000
Annual Operating Cost	**$13,263,208**
Material usage	$2,193,000
Utilities	$62,000
Environmental compliance	$54,208
Maintenance and labor	$10,954,000

The following assumptions were used in comparing the process costs of the two coating systems:

- All cost values are based on calendar year 2007 dollars.
- All cost figures are based on cost to performing company.
- The equipment design costs, material formulation, and demonstration and validation estimated costs for the baseline process would not require any additional cost because the process is already established.
- Estimated design cost for the UV curable process is estimated at 30 ± 20% of total equipment purchase costs.
- Equipment integration estimated costs for both processes are estimated at 50 ± 30% of total equipment purchase costs.
- The annual operating costs of both coating systems are based on the data presented in Table 3.
- UV curable demonstration and validation costs are actual costs.

- Costs for the robotic spray systems and UV lamps for the UV curable process are estimated based on costs incurred during the demonstration and validation.
- Costs for the baseline robotic spray system are actual costs.

Table 4 shows a potential significant reduction in operating costs of the UV curable coating system. The infinite pot life of the UV curable system has the potential to eliminate the need to flush out the gun every 15 applications, which would reduce hazardous waste disposal and material usage. The absence of solvents in the UV curable system further has the potential to reduce the material usage as well as the frequency with which the hardware and filters must be changed. The estimated reduction in cure time of the UV curable system has the potential to reduce the cycle time, which in turn reduces labor, energy, and paint booth usage. Several other cost benefits that cannot be quantified here are expected to result from the implementation of the UV curable coating system.

5.3.1 Life-Cycle Cost Analysis

A life-cycle cost analysis was performed using the data from Table 4. The objective of this analysis is to determine the potential for the UV curable coating system as an economically viable alternative to the baseline coating system. The life-cycle cost evaluation was calculated by totaling the estimated initial investment required as well as the estimated annual recurring costs over the expected 15-year life of the equipment. Per ECAM guidance, this approach performs the following:

- Estimates the annual cash flows using the cost data described above
- Discounts future cash flows for the time value of money
- Calculates financial performance measures (net present value[NPV] and internal rate or return)
- Compares these measures with acceptance criteria.

A summary of the estimated delta life-cycle cost savings associated with the UV curable coating system is provided in Table 5.

Table 5. Estimated Life-Cycle Cost Analysis.

Coating System	Delta Installation Cost	Delta Annual Operating Cost	Delta Life-Cycle Cost
Delta UV curable cost from baseline	-$9,832,000	$13,263,208	$189,116,120

Three performance measures for investment opportunities were then considered in the ECAM evaluation: payback period, NPV, and internal rate of return (IRR). The payback period is the time period required to recover all the capital investment with future cost avoidance. NPV takes this investment-return analysis one step further by calculating the difference between capital investments of the two coating systems and the present value of future annual cost benefits associated with the UV curable coating system. This value represents the life-cycle cost associated with the UV curable coating system. The IRR is the discount rate at which NPV is equal to zero.

NPV and IRR account for the time value of money and discount the future capital investments or annual cost benefits to the current year. For NPV and IRR, a 4% discount rate and a 15-year life-cycle period was used for this financial evaluation. The 15-year estimated net present value, estimated internal rate of return, and estimated discounted payback period for the UV curable system are shown in Table 6. Table 7 summarizes the investment criteria used to determine whether the UV curable system is a financially viable alternative to the baseline coating system.

Table 6. NPV, IRR, and Discounted Payback Period for the UV Curable Coating System.

NPV	IRR	Discounted Payback Period
$137,633,485	134.90%	0.74 years

Table 7. Summary of Investment Criteria.

Criteria	Conclusions
NPV > 0	Investment return acceptable
NPV < 0	Investment return not acceptable
IRR > discount rate	Project return acceptable
IRR < discount rate	Project return not acceptable

The estimated NPV value for the UV curable coating system is positive, and the estimated IRR is greater than the discount rate, which, based on the investment criteria in Table 7, means that implementation of the UV curable coating system is potentially an economically viable alternative to the baseline coating process. Therefore the UV curable coating system has the potential to provide a higher value to the facility than the baseline coating system.

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6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

The robotic application equipment and cure equipment were designed and developed under an effort summarized in Appendix A of the Final Report. This funding was utilized to support and facilitate the transition of the technology to a weapon system.

The UV curable material costs more per gallon of material; however, the overall quantity of the UV curable material is less than the baseline material. The baseline material contains VOCs and exempt solvents, which flash off after applications. However, with the UV curable system, there are no VOCs and no solvents; therefore, the wet film thickness of the material is equivalent to the dry film thickness of the material, thus reducing material volume loss.

The largest cost associated with this project is the capital cost for a robotic spray booth facility and the associated environmental equipment. Since the cost evaluation of implanting the spray booths is so complex and has multiple variables as well as multiple configurations and options, this is the area where the cost evaluation can have the greatest fluctuations. A thorough cost analysis and spray booth design is needed to fully capture the true cost of implementation.

6.2 PERFORMANCE OBSERVATIONS

The test results are summarized in Table 1. Overall, the material meets most of the material requirements. This demonstrates that the material has potential as a viable replacement for the baseline material. The material adhesion following fluid exposures to MIL-DTL-83133 (JP-8) and MIL-PRF-85570 Type II (alkaline cleaner) showed some deviation from the material requirements. The test coupons exposed to the alkaline cleaner were tested and resulted in tensile strength that deviated less than 10% from the goal. This deviation in performance may be due to the test method used for these specific test coupons. The test method defines a test speed of 0.1 in/min; however, these coupons were tested one order of magnitude lower at 0.01 in/min due to an error by the lab technician. Since the adhesion testing of the UV curable material following these exposures were within 10% of the requirement, it is likely that the testing of the material at the correct test speed would yield results that meet the material requirements. The UV cured material will be retested under alternate funding to establish the material adhesion following exposure to MIL-PRF-85570.

Following exposure to JP-8 the material failed the flatwise tensile test. These coupons were tested with the same method as described in the paragraph above. This discrepancy in test method may account for some of the loss of adhesion; however, the test method is not the only factor affecting the material's adhesion following fluid exposure. Additional testing will be performed on test coupons following MIL-DLT-83133 exposure, and this issue will be addressed in an effort summarized in Appendix A of the Final Report.

The compatibility of the material with the baseline material was also an area where the UV curable material did not meet the full requirement. Again, flatwise tensile strength was used as the test method to demonstrate material compatibility to the baseline material. The same discrepancy in test speed was repeated in this testing. Also, the results showed partial adhesive failures to the pull member bonded onto the UV curable material for test. This shows failure of the surface preparation to the test coupon, which does not represent the platform application. These two factors are potentially large factors that would affect the tensile strength results from the testing. These test configurations will be retested under alternate funding to establish the UV repair material adhesion.

Once the adhesion properties can be verified, the UV curable material could be used as a viable alternative to the baseline coating and repair material. The UV curable coating provides significant benefits in reductions of cycle time, VOC and HAP emissions, and overall cost.

6.3 SCALE-UP

Robotic application is dependent on development of a cure system for this type of large-scale application. Without development of the application and cure equipment, this process is not a viable technology for transition for this specific application. This robotic application, UV lamp and material scale-up issue are being addressed in an effort summarized in Appendix A of the Final Report to develop the equipment.

6.4 OTHER SIGNIFICANT OBSERVATIONS

UV curable materials can provide great benefits to the original equipment manufacturer (OEM) and depots, but the equipment is the key factor in the implementation of the technology. Without adequate cure equipment, the UV technology cannot be used for repair or for OEM application. Along with the development of UV cure equipment is the safety and UV exposure concerns that need to be addressed with the implementation of the UV technology. Since this is a new technology for the aerospace industry, many hurdles from those who are not aware of the UV technology will have to be overcome for implementation. With time and a more widespread understanding and knowledge of the technology, UV could be part of the future of the aerospace industry.

6.5 LESSONS LEARNED

This demonstration of the UV curable coating was a successful demonstration of UV curable technology for aerospace application. Prior to this demonstration, UV cure technology has not been used for aerospace application. This demonstration was useful in proving that UV curable technology could be a viable technology aerospace application, as long as the correct application is chosen.

One key in the successful demonstration is the coordination and attendance of the end users and key government personnel for the demonstration. Without the participation of both the end users and the government personnel, many ideas and potential technical concerns would not have been addressed during this demonstration.

6.6 END-USER/ORIGINAL EQUIPMENT MANUFACTURER (OEM) ISSUES

End users include Northrop Grumman, Lockheed Martin, and Boeing. The optimization/baseline testing as well as the demonstration/validation will address a number of potential concerns:

- Ability of the UV cured material to meet the baseline platform requirements
- Potential manufacturing cycle time reduction
- Ability to spray apply and cure a UV coating
- Performance impact of the repair UV curable coating on the baseline material
- Validate that the material can be spray-applied and cured in order to demonstrate compatibility with baseline materials
- Demonstrate that the filled material is appropriate for field use by showing that the material can be used to repair the current baseline material while maintaining the overall aerospace performance characteristics
- Time and labor needed to implement this method and identify if there is any interference with present methods and schedules
- Cost-benefit analysis (primarily labor for application process, equipment, reduction in amount of material usage, and VOC emissions)
- Safety concerns about UV exposure during cure.

The equipment to be used for testing is a custom built prototype that will be developed by Pratt Whitney Automation for the robotic application, and a commercial off-the-shelf UV curing system built by Fusion UV.

The robotic application system will be tailored to specifically apply the material being tested to the parameters determined during the material development phase of this effort. The design and fabrication of the integrated system will be performed under the effort summarized in Appendix A of the Final Report.

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7.0 REFERENCES

Demonstration/Validation Plan of WP-0408, www.estcp.org.

ESTCP Project WP-0303, www.estcp.org.

SERDP Project WP-1181, www.serdp.org.

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APPENDIX A

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ACRONYMS AND ABBREVIATIONS

CAA	Clean Air Act
DCAA	Defense Contract Audit Agency
DoD	Department of Defense
DSS	Defense Security Services
ECAM	Environmental Cost Analysis Methodology
ESTCP	Environmental Security Technology Certification Program
FMI	Foster Miller Inc.
HAP	hazardous air pollutants
HAZMAT	hazardous material
HF	Hydrofluoric Acid
IRR	Internal Rate of Return
NESHAP	National Emissions Standards for Hazardous Air Pollutants
NGC	National Guideline Clearinghouse
NPV	Net Present Value
OEM	original equipment manufacturer
P2	pollution prevention
PUVD	polyether/polyurethane oligimer
PWA	Pratt & Whitney Automation
RCRA	Resource Conservation and Recovery Act
RTO	regenerative thermal oxidizer
SAM	surface-to-air
SERDP	Strategic Environmental Research and Development
UCAV	unmanned combat air vehicle
UV	ultraviolet
VOC	volatile organic compound

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ACKNOWLEDGEMENTS

This report was prepared by Madeleine Low, Northrop Grumman Corporation, El Segundo, California, under project number WP-0408 for the Environmental Security Technology Certification Program (ESTCP).

The following organizations provided invaluable contributions to this document:

- Air Force Research Laboratory, Dayton, Ohio
- Boeing Aerospace, St. Louis, Missouri
- Environmental Security Technology Certification Program
- Foster Miller Incorporated, Waltham, Massachusetts
- Fusion UV Systems, Gaithersburg, Maryland
- Lockheed Martin, Fort Worth, Texas
- NavAIR, Patuxent River, Maryland
- Pratt and Whitney Automation, Huntsville, Alabama
- Universal Technology Corporation, Dayton, Ohio

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1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

Elastomeric coatings used for aerospace applications typically contain volatile organic compounds (VOC) and hazardous air pollutants (HAP) such as methyl ethyl ketone, methyl isobutyl ketone, toluene, or xylene at levels as high as 600 g/L. Despite this fact, these coatings are currently exempt from 1998 National Emissions Standards for Hazardous Air Pollutants (NESHAP) due to the lack of a suitable low-VOC substitute as well as their low usage volume at the time the regulation was drafted and passed. Since that time, the requirement for use in aerospace applications of these coatings has substantially increased. Over the next decade, the U.S. military plans to deploy several new weapons systems that use elastomeric coatings and technology to retrofit several existing systems, including the use of elastomeric coatings to improve the performance of the aircraft. As a result, the emission of VOC from elastomeric coatings is expected to increase to about 2 million pounds per year.

In addition to environmental issues, the process for applying elastomeric coatings is time and labor intensive due to the relatively thick coatings that are applied. The required thickness is achieved by applying multiple layers. Applying these coating to an aircraft or missile weapon system is a very cumbersome process and usually requires multiple shifts.

The objective of this program is the demonstration and validation of innovative technologies that will result in a nearly 100% reduction of VOC emissions from an elastomeric coating spray application. The coating resin used in this program was developed by Foster-Miller, Inc. (FMI) in part under Strategic Environmental Research and Development (SERDP) funding (WP-1180). This specific resin was chosen based on its potential ability to allow cure of thick layers of filled formulations. The ultraviolet (UV) coating technology has the potential to provide 90% reduction in application and cure time, thus reducing life-cycle costs tremendously and improving mission readiness of the aircraft.

1.2 OBJECTIVES OF THE DEMONSTRATION

The objective of the project demonstration was three-fold:

1. Demonstrate that the FMI UV curable resin can be tailored to meet specific weapon system requirements through the addition of appropriate fillers and additives
2. Validate that the material can be spray-applied and cured in order to demonstrate compatibility with production and field application methods
3. Demonstrate that the coating is amenable to field repair and the repaired coating maintains its aerospace performance characteristics.

1.3 REGULATORY DRIVERS

The need to reduce pollution is driven by regulatory issues and government policies. NESHAP has been the principal compliance driver over the last decade for the aerospace industry, in particular NESHAP 40 CFR Part 63. Hazardous material (HAZMAT) reduction is driven by the Clean Air Act (CAA) and Resource Conservation and Recovery Act (RCRA) through pollution prevention (P2) efforts. Many P2 projects impact both CAA and RCRA concurrently. Examples are:

- CAA: Solvent substitution replacing high vapor pressure solvents with compliant, lower vapor pressure chemicals, utilizing non-VOC and/or non-HAP solvents and coatings, powder coat applications vs. conventional coating, etc.
- RCRA: Reducing or eliminating toxic/corrosive/flammable/reactive waste streams through material substitution, increasing recycling efforts for solid waste, etc.

Both the CAA and RCRA mandate either directly or indirectly that efforts to minimize pollution be instituted. The CAA under the NESHAP 40 CFR Part 63 places restrictive limits on material use. Most Department of Defense (DoD) coatings fall under the NESHAP regulations although the coatings addressed here are exempt because of their application. However, VOC limitations are often placed on manufacturing and repair facilities based on the limits of their operating permits and can therefore restrict operations. Further, the baseline coatings typically contain large quantities of solvents that in many cases are considered to be hazardous air pollutants. The UV curable coatings eliminate solvents and HAPs thereby facilitating compliance with air quality regulations at DoD manufacturing and repair facilities.

When signing a Hazardous Waste Manifest, the generator declares that they have a program in place to reduce the volume and toxicity of waste generated to the degree determined to be economically practicable. This minimizes the present and future threat to human health and the environment. The UV curable coating technology eliminates hazardous waste by reducing toxicity and volume of paint-related waste. First, the fact that material is a single component eliminates much of the waste associated with mixing and applying the coating (eliminates pot life constraints). Second, eliminating the solvents and hazardous components (such as free diisocyanate) reduces the toxicity of the waste stream. Further, since the waste that is generated doesn’t contain solvent, it is considered to be nonflammable.

When compared to the baseline materials, the UV curable coatings offer several environmental benefits:

- Eliminate VOC, HAP, and free diisocyanates from the coatings, thereby eliminating many of the employee health and safety issues associated with conventional coatings
- Eliminate VOC, HAP, and free diisocyanates from the coatings, thereby reducing facility emissions of VOC and HAP.
- Eliminate HAPs and free diisocyanates from the coatings, thereby reducing toxicity of waste streams.
- Eliminate waste associated with material mixing and pot life, thereby reducing the quantity of waste generated.

1.4 STAKEHOLDER/END-USER ISSUES

The demonstration will validate the feasibility of using UV curable materials in aircraft design as well as demonstrate the repairability of the coating. However, because of the current constraints associated with large-scale application of the coatings, many of the stakeholder issues cannot be addressed at this time (note that the application and cure equipment scale-up was identified as an option task in the original proposal). Due to the complexity of developing an elastomeric coating, the demonstration will be directed toward a specific platform with potential transitions to multiple platforms.

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2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

UV curable coatings are a new technology for the aerospace industry, and recent advances in photoinitiators and light sources have enabled the cure of both thick and filled coatings, thereby thrusting UV coatings to a heightened level of practicality. FMI has adapted this new technology and has demonstrated that a vinyl dioxolane terminated polyether/polyurethane oligimer (PUVD) combined with a variety of fillers can be cured at thicknesses of 1-4 mils (depending on the filler used) with UV irradiation in less than 30 sec with negligible change in thickness, thus resulting in significant reduction of time per pass compared to the conventional solvent-borne systems. The fillers along with the required proportions used in the SERDP program were supplied by the Boeing Company. FMI has also shown the ability of these filled PUVD layers to be applied one at a time to build up the required thickness levels (30–100 mils) for specific applications. The resulting coatings showed excellent interlayer adhesion. The proposed technology offers the following significant advantages over the current coatings used for signature management:

- Minimal shrinkage in the “as applied” wet film results in improved dimensional control.
- Cure time per pass is reduced from 15 min to 30 sec.
- VOCs, HAPs and free diisocyanates are eliminated.
- The coating can be supplied as a one-component system, thus eliminating time and error associated with mixing as well as minimizing the waste associated with unused material.

FMI’s coating was demonstrated on a laboratory scale and has considerable promise for transition to several weapon systems. The current program will provide a means of carrying the technology to the next stage through process scale-up and will provide an understanding of the performance aspects of the coating in field applications. As a result, we anticipate building an awareness of the technology in the aerospace community to ease transition to various platforms for all branches of DoD.

2.2 PROCESS DESCRIPTION

UV curable coatings require two things for applications:

1. Application equipment
2. Curing equipment.

For this application, FMI’s UV curable material was applied using two different techniques. The first technique used robotic spray application equipment. Many coatings are now being robotically spray-applied to the specific aircraft parts. For this demonstration of this application, a standard robotic spray system was modified to allow for the spray application of the UV curable material. Due to the high viscosity of the material, the material must be heated for spray applications. Therefore, the robotic fluid delivery system was modified to include heated fluid lines and a heated material pot. The heated fluid delivery system is shown in Figure 1.

Typical aerospace coatings are multi-part kits, (base and catalyst are in separate containers); however, the UV curable material is a single component material kit, with no additional catalyst required, therefore, the fluid delivery system was further modified for a single component application.

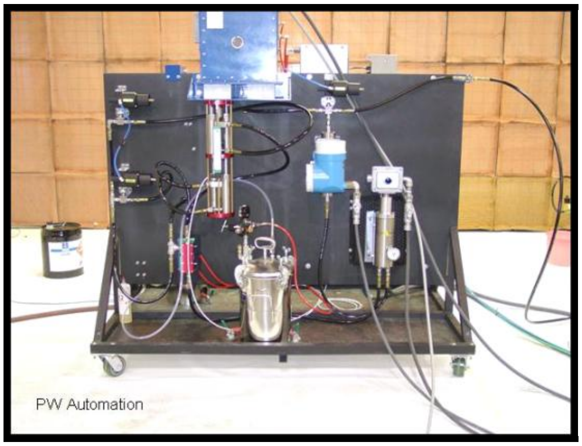

Figure 1. Single Component, Heated Fluid Delivery System.

The second application technique used to demonstrate the UV curable material was a hand repair method. For the repairs, the material would be put in the repair area, and smoothed to the desired thickness using specific tooling. After the material was applied to the desired thickness, the repair panel was cured and the next layer of material was applied using the same technique. For this method, multiple drawdown blades were fabricated with various standoff distances from the surface to control material application thickness. The tooling and equipment used for this method is shown in Figure 2.

Figure 2. Repair Tools.

To cure the UV curable materials, two cure apparatuses were used. The first apparatus was a floor-standing conveyor belt cure system, shown in Figure 3. This system was developed for laboratory curing of test coupons. It is capable of curing specimens up to 24-in-wide and the height of the lamps is adjustable for up to 6-in high. Also, the conveyor belt speed is variable based on the required exposure time to the UV light. The conveyor is equipped to cure using two types of curing bulbs in series. The system used air flow to provide cooling during the cure process.

Figure 3. Floor-Standing Conveyor UV Curing System.

The second cure apparatus used was a robotically mounted UV lamp system. This system was designed specifically for this demonstration to enable cure of a large-scale part. The mounted UV cure lamp is shown in Figure 4. This system has the capability of using one UV curing lamp at a time. The UV lamp stand-off and speed were controlled by the robotic control system. Since the robotic system was located in an open spray booth, a UV shielding curtain was installed around the spray booth to protect both the operators and the observers from exposure to high levels of UV irradiation.

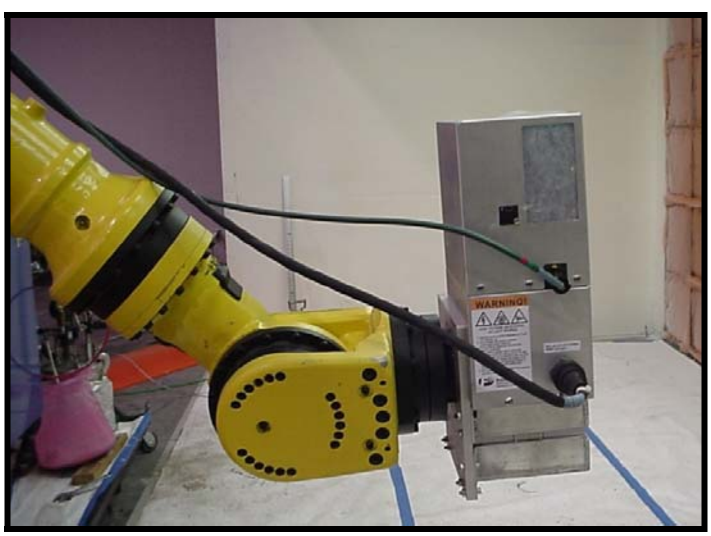

Figure 4. Robotically Mounted UV Curing System.

The application and cure equipment described above was used to apply the UV curable coating to various substrates. These substrates were then tested per various military standards described in the Demonstration Validation Plan.

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

Significant prior testing of the UV curable coating occurred under the SERDP Project WP-1181 by Foster Miller. The SERDP WP-1181 project was a 4-year effort started in FY 2001 and concluded in FY 2005. The material development and testing was performed by Foster Miller in Waltham, Massachusetts, and the material testing was performed at both Foster Miller and Boeing Phantom Works in St. Louis, Missouri. The testing protocol and the results of the testing can be found in the Final Report for the SERDP WP-1181 project found on the SERDP website.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The FMI UV curable coating developed has numerous benefits when compared to the baseline coating, including elimination of VOC emissions and hazardous waste and reduction of cycle time, labor, and capital assets.

Baseline Material and Process – The baseline coating is a multicomponent, polyurea resin with solvents and fillers, with a VOC of approximately 432 g/L. Current spray operations at Site 4, Plant 42, have a robotic spray system for applying the baseline material. The current material requires approximately 22 hours of application time per shipset. This time is predicated by several factors including material application thickness per pass, coating shrinkage due to solvent evaporation, coating dwell between coating layers, and travel time for the application robot to apply the coatings. There is also a 5-day dwell between the material application and the primer coating application to allow for solvent flash.

VOC Elimination – FMI's UV curable coating is a single component system that contains only a small amount of reactive diluents for viscosity reduction. Reactive diluents are not emitted during spraying but rather become part of the polymer upon cure. This results in a zero VOC coating. This eliminates over 1.7 million lbs of VOC emissions for the current projected order of aircraft. With a potential equivalent quantity of projected foreign military sale aircraft, the total VOC reduction will be over 3 million lbs of VOC emissions. Since zero VOC coatings are also exempt from all the environmental reporting and tracking requirements, that will reduce labor costs.

Hazardous Waste Elimination – The coating does not cure without intense UV irradiation. This will result in not requiring that the spray systems be purged and flushed with solvent between work shifts or between plane spray operations. This should have a major impact on the amount of hazardous waste associated with solvent flushing of the baseline coating, which cures within a few hours after mixing. The materials used for the coating have Draize values less the 1.8 and the fillers in the UV curable coating are nonhazardous, thus the coating does not require any additional special handling. UV curable coating waste can be cured and the waste will contain no unreacted solvent so the material can be disposed of as nonhazardous waste.

Cycle Time Reduction – FMI has developed a UV curable coating that can significantly reduce the long application and cure cycle time while meeting stringent property requirements for aerospace applications. It is anticipated that the UV curable coating and UV cure process will significantly reduce the 22-hr application cycle time and 5-day curing cycle time for coating the specific application. The UV curable material can be applied at coating thickness ranging from 10-20 mils per pass, and there is no shrinkage as the coating is 100% solids (no VOC) with minimal reactive diluents. The coating is fully reacted upon irradiation, so there is no dwell time required between passes. The only unknowns currently are the changes to the robot path planning to accommodate the new coating and the time and mode for the irradiation process.

The new spray process is capable of building an average of 15 mils dry per coating layer, while eliminating the 10-min dwell between layers. There are three additional advantages to cycle time reduction associated with the rapid cure nature of UV coatings. Instantly after coating cure you can perform thickness measurements and begin sanding. It also eliminates the 5-day dwell for solvent flash before applying the primer and topcoat.

Capital and Recurring Labor Savings – These factors will significantly impact the cycle time and work flow processes, which will minimize the number of spray booths, sanding booths, and cure areas at full-rate production levels. In fact, the UV cured material application should be able to be performed in a non-VOC controlled spray area if facilities can accommodate such an arrangement. Recurring labor will be significantly reduced as a result of the higher build rate, reduced environmental reporting requirements, and elimination of the need to mix the coating (one component). Further, the infinite pot life of the UV curable coating will potentially eliminate the need to solvent flush the system between coating operations. These solvent flushes are currently being used to ensure that material does not build up in the fluid lines and when the material has passed its pot life.

Other Reduced HAP/VOC Aerospace Elastomeric Coatings Efforts – There are multiple programs targeting the reduction of HAP and VOC emissions in various aerospace application, including the ESTCP project WP-0303. The WP-0303 effort is targeted at decreasing labor hours, reducing production and maintenance cycle times, reducing VOC emissions by 75% and mitigating material usage and waste generation. Though the WP-0303 effort's target is to reduce the VOC emissions, the UV curable materials effort will eliminate VOC emissions completely. Also, the WP-0303 program is evaluating materials that that utilize the same cure mechanism as the current material, while the UV curable materials program is looking at utilizing UV curable materials, thus has a potential for a greater reduction in production cycle time. More information on the WP-0303 project can be found on the ESTCP website.

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3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

There objectives of the technology demonstration are 1) demonstrate that the UV curable resin can be tailored to meet specific weapon system requirements through the addition of appropriate fillers, 2) validate that the material can be spray-applied and cured in order to demonstrate compatibility with production and field application methods, and 3) demonstrate that the filled material is appropriate for field use by showing that the material can be repaired and maintain its aerospace performance characteristics. The performance objectives and actual performance for this project can be found in Table 1.

Table 1. Performance Objectives.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance
Quantitative	1. Reduce VOC	98% reduction	Pass
	2. Cure time	30 sec/pass	Pass
	3. Specific gravity*	Requirement defined in Final Report	Pass
	4. Ultimate tensile strength	Requirement defined in Final Report	Pass
	5. Elongation @ break	Requirement defined in Final Report	Pass
	6. Flatwise tension	Requirement defined in Final Report	Pass
	7. Flexibility	Requirement defined in Final Report	Pass
	8. Intracoat adhesion	Requirement defined in Final Report	Pass
	9. Chemical resistance	Requirement defined in Final Report	Pass
	10. Heat resistance	Requirement defined in Final Report	Pass
	11. Salt fog	Requirement defined in Final Report	Pass
	12. Humidity resistance	Requirement defined in Final Report	Pass
	13. Fluid resistance	Meets adhesion and flexibility requirement defined in Appendix B following exposure to:	
		MIL-PRF-87252	Pass
		MIL-DTL-83133	Pass flexibility Fail adhesion
		DIL-PRF-83282	Pass
		MIL-PRF-23699	Pass
		ASM 1424 TYPE 1	Pass
		AMS 1435	Pass
		DOD-L-85734	Pass
		MIL-PRF-85570	Pass flexibility Fail adhesion by less than 10%
		DI water	Pass
	14. Time to Full Cure	Requirement defined in Appendix B	Pass
	15. Compatibility	Compatible with baseline material	Fail adhesion by less than 25%
	16. Platform performance*	Requirement defined in Appendix B	Pass
Qualitative	1. Less complex repair application	Time to apply and cure	Pass

* NOTE: This information is considered Northrop Grumman/Platform proprietary and is not available for distribution.

A detailed discussion of the actual performance of the UV curable material can be found in Section 6.2.

3.2 SELECTING TEST PLATFORMS/FACILITIES

During the first phase of the contract, several platforms were considered for application of FMI's UV curable coating technology. Ultimately, a specific platform was selected as the target platform because of its specific requirements surrounding the application of an elastomeric coating. The elastomeric coating is applied as multiple layers to obtain a final coating thickness that is thicker than typical coatings, such as primers and topcoats. Currently, the application and cure of the baseline material is driving the aircraft production schedule. By tailoring FMI's UV curable coating to this application, the cycle time associated with the coatings application can be substantially reduced. Northrop Grumman is currently working (under separate contract) with FMI, Pratt & Whitney Automation (PWA) and Fusion to scale up the robotic application and cure equipment. Currently, the majority of the resources required for the demonstration (spray and cure equipment) are located at PWA. The demonstration will be conducted in two phases and the responsibilities will be split between the companies.

- FMI will provide the raw material for the demonstration and provide technical personnel to assist with spraying and curing the coating.
- PWA will provide the spray equipment and technical support personnel to operate the spray and cure equipment.
- Northrop Grumman will provide the conveyor cure equipment (currently located at PWA), substrates to which the UV curable coating will be applied, and technical personnel to support the application and cure of the UV curable coating to the substrates. Northrop Grumman will be responsible for defining the test coupon configurations.
- Fusion will provide the portable cure equipment and technical personnel to support the cure of the UV curable coating to the substrates.

3.3 TEST PLATFORM/FACILITIES HISTORY/CHARACTERISTICS

The facility chosen for the demonstration and validation is PWA in Huntsville, Alabama (formerly CTA). This division of Pratt & Whitney's Advanced Systems Technology Inc. is a world-class robotic system integrator specializing in precision coating, coating removal, robotic manufacturing, material handling systems, and turnkey industrial robotic systems. PWA is an industry leader with the ability and expertise to customize processes and systems. As the industry leader in automation of weapon system manufacturing processes, PWA has provided robotic systems for manufacturing ground vehicles, surface-to-air (SAM) missile systems and munitions. The facility is Defense Security Services (DSS) and Defense Contract Audit Agency (DCAA) approved.

PWA provides engineering, design, validation, installation, training, and maintenance of automated manufacturing technology for an entire manufacturing facility or for a single coating or coating removal system. PWA technical and engineering personnel have a long history of successfully integrating automated systems into new or existing manufacturing environments. PWA provides conveyors, robots and reciprocators, coating or coating removal equipment, spray booths, cure ovens, part fixtures, and computer controls and has brought its experience in automated system integration to the production coating of unmanned combat air vehicles (UCAV), missiles, munitions, space vehicles and F-22, F-18, F-35 and B-2 coating applications.

3.4 PHYSICAL SETUP AND OPERATIONS

The spray and repair using FMI's UV curable material was demonstrated on December 5-6, 2006, at PWA. Following the demonstrations, test coupons were sent to National Guidance Clearinghouse (NGC) for material performance testing to validate the demonstration objectives. Testing was completed on March 16, 2007. The robotic application and conveyor system cure system were designed for application onto the test panels at approximately 20 mils per pass. The robotic application system had a heated material pot, heated fluid lines, and a heated pump. Unlike the baseline material, the UV curable material must be heated to reduce the viscosity of the material for spray application. For a large-scale test coupon, the UV lamp was set up to be mounted onto the robot system. This allowed for horizontal movement of the robot, which allowed for a large-scale test panel to be cured with the existing UV lamp system.

3.5 SAMPLING/MONITORING PROCEDURES

The robotic applications and cure procedures are outlined in the Demonstration and Validation Plan for this effort. The test coupons fabrication and testing performed for the validation are also defined in the Demonstration and Validation Plan. Please refer to that document for specific procedures and processes.

3.6 ANALYTICAL PROCEDURES

The data collected during the demonstration and validations was compared to the baseline material properties of the current material used in this application to verify that the material meets the platform requirements. The specific platform has provided input as to the acceptability of the material performance, and a pass/fail result is reported in this report.

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4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE DATA

Table 1 summarized the results of the validation testing. The validation testing shows that FMI's UV curable material meets or exceeds most requirements set forth for the material. The full test results and data were provided to the specific platform for analysis and approval. Additional discussion of the UV curable material performance can be found in Section 6.2.

4.2 PERFORMANCE CRITERIA

See Table 2 for Performance Criteria.

Table 2. Actual Performance and Performance Confirmation Methods.

Performance Criteria	Expected Performance Metric	Performance Confirmation Method	Actual Performance
PRIMARY CRITERIA (Performance Objectives) (Quantitative)			
Product testing	*Pass the testing defined in Final Report*	*Test method defined in Final Report.*	**Pass majority of requirements**
Hazardous materials -VOC emission reduced - Generated	*No hazardous waste is introduced by this technology.* *Non generated*	*VOC test method defined in Final Report.*	**Pass**
Process waste	*No process waste is introduced by this technology.*	*Operating experience*	**Pass**
Factors affecting technology performance	*Spray application and cure process will provide specimens without porosity or layering and with acceptable surface finish.*	*Cross-section analysis of the sprayed coating.*	**Pass**
SECONDARY PERFORMANCE CRITERIA (Qualitative)			
Ease of use	*Robotic operator will be trained for use of equipment.*	*Operating experience*	**Pass**
Reliability	*Robotic material application will not be affected by equipment.*	*Operating experience*	**Pass**
Versatility	*Robotic material applications will be performed on small test coupons.*	*Operating experience/Assessments*	**Pass**
Maintenance	*Setup, operating, and breakdown procedures can be designed for easy operation.*	*Operating experience/Assessments*	**Pass**
Scale-up constraints	*Scale-up will be evaluated on the effort summarized in Appendix A.*	*Operating experience/Assessments*	**Pass**

The Data Assurance/Quality Control Plan for the demonstration can be found in Appendix D.

4.3 DATA ANALYSIS, INTERPRETATION, AND EVALUATION

The data collected during the demonstration and validation was compared to the baseline material properties of the current material used in this application to verify that the material meets the platform requirements. The specific platform has provided input as to the acceptability of the material performance, and a pass/fail result is reported in this report.

4.4 TECHNOLOGY COMPARISON

The technical performance of FMI's UV curable material is summarized in Table 2 and the Final Report. Based on these results, the FMI UV curable material has equivalent or better technical performance when compared to the baseline coating for most of the material requirements. The requirements that were not met in this demonstration are discussed in Section 6.2. The greatest difference between the two coatings comes when looking at the environmental and cost drivers. Based on the analysis presented in this report, there are both environmental and cost advantages in using the FMI UV curable coating.

There are other programs targeting the reductions of HAP and VOC emissions in aerospace coatings, including the ESTCP project WP-0303. The WP-0303 effort is targeted at decreasing labor hours, reducing production and maintenance cycle times, reducing VOC emissions by 75%, and mitigating material usage and waste generation. Though the WP-0303 projects effort target is to reduce the VOC emissions, the UV curable aerospace materials effort will eliminate VOC emissions completely. While the WP-0303 program evaluates materials that utilize the same cure mechanism as the baseline material, the UV curable program evaluates materials that utilize a UV cure mechanism and has a potential for a greater reduction in cycle time. More information on the WP-0303 project can be found on the ESTCP website.

5.0 COST ASSESSMENT

5.1 COST REPORTING

The Environmental Cost Analysis Methodology (ECAM) tool is designed to facilitate the gathering and analysis of economic data in a manner that allows for more accurate evaluation of investment—especially when used for pollution prevention technologies. Typical cost analysis efforts often overlook significant costs, especially environmental costs.

For this effort, the application, cure equipment, and process are being developed under the effort summarized in Appendix A of the Final Report; therefore the full ECAM analysis cannot be completed at this time. The cost analysis will use the available data and estimates required to perform a cost analysis based on ECAM. This information will be used to provide information for the cost factors described in the Final Report, Section 2.3.

5.2 COST ANALYSIS

This cost analysis is based on the replacement of the baseline material and material application equipment with the UV curable material, application, and cure equipment. All costs are based on estimates and approximations made using the current knowledge of the current and proposed application processes.

All cost and rates are estimates and are used for planning purposes only. All cost figures are based on the cost to the performing company. All estimated cost values are based on calendar year 2007 dollars.

5.2.1 Cost Drivers

For the analysis of this technology, the cost drivers included the following: capital cost, material usage, utility usage, labor usage, facility usage, equipment maintenance, hazardous waste disposal, recurring environmental compliance costs, and the effect of cycle time on other phases of production.

5.2.2 Cost Basis

For the cost assessment, the UV curable coating is assumed to replace the baseline coating that is applied at the Northrop Grumman assembly line at Air Force Plant 42, Palmdale. The cost data was obtained from a survey of the transition to production effort that was undertaken for the baseline material and from data accumulated throughout the demonstration and validation of the UV curable coating.

Northrop Grumman is currently planning to build a facility in Palmdale capable of applying coatings at the expected high-volume production rate. Consequently, baseline operation and capital costs for full-rate production are estimated, and both must be considered in this cost analysis. The estimates for the full-rate production costs were obtained from a study by Comau Pico, a Detroit-based automotive systems integrator. Comau Pico produces the most advanced automotive assembly lines in the world. Comau Pico performed the following tasks to determine the lowest cost for the baseline coating process:

- Define ground rules and assumptions
- Develop facility layouts for proposed manufacturing sites
- Throughput simulation and analysis for proposed manufacturing plans
- Tooling assessments, recommendations, and impacts
- Equipment listing
- Time phased booth implementation based on production schedule
- Cost assessment—budget schedules and recommendations with assumptions for capital equipment, facility upgrades, and recurring costs
- Risk assessments and capital resource mitigation
- Down select of booth infrastructure concepts, manufacturing plans, and costs
- Specifications for accepted concepts.

Included in the capital and recurring cost associated with adding the full-rate production capability is the addition of multiple robotic spray booths. For each of the spray booths, the appropriate environmental filtration systems need to be installed. For this application, carbon adsorption filters and regenerative thermal oxidizers (RTO) will be required in the spray booths to prevent emission of VOCs into the atmosphere.

At the facility multiple coatings will be applied in each spray booth, including the baseline material for which the UV curable material is being evaluated as a replacement. One of the coatings that will be robotically sprayed contains Oxsol® 100 (PCBTF) in the formulation. Based on chemical analysis, the Oxsol® in the material will react with the RTO and produce Hydrofluoric Acid (HF), which is a hazardous acid and will erode the RTO with time. Therefore, carbon adsorption filters must be added to the system to mitigate the problem. The carbon adsorption filters will react with the Oxsol® prior to entering into the RTO, thereby eliminating the production of HF.

Though the carbon adsorption filters will eliminate the HF byproducts, the carbon adsorption filters preferentially absorb acetone. There is a high level of acetone in the current baseline coating formulation (the coating that the UV curable material is targeting to replace). The preferential adsorption of the acetone would increase the frequency with which the carbon adsorption filters must be changed. Two configurations have been evaluated to address the environmental filtration systems:

- **Option 1 –** Equip all spray booths with both RTO and carbon adsorption, and maintain the capability to spray the all material in every booth.
- **Option 2 –** Spray the materials containing Oxsol® and acetone in separate booths.

With the current materials, Option 1 may increase the frequency with which the filters must be changed, and Option 2 has the potential to decrease the frequency with which the filters must be changed but may increase the number of booths required. Currently, the baseline plan is to implement Option 2. This would restrict the use of booths to the specific material that is designed into the environmental filtration system, and may increase the number of spray booths needed to meet the full-rate production needs. With this potential increase in spray booths, there will be an associated increase in capital cost.

The UV curable material is developed to replace the material containing acetone. With the implementation of the UV curable coating, the acetone adsorption by the carbon adsorption filters would no longer be an issue. This could potentially reduce the number of spray booths by eliminating the need for material-specific booths, which potentially reduces the total number of spray booths needed, reducing capital and operating costs. The full benefits of using the UV curable alternative cannot be fully defined without further investigation by the EPA to determine the full filtration system required for this coating.

Since the UV curable replacement material is a zero VOC coating, the implementation of the UV curable replacement has the potential to reduce the capital and recurring cost of the environmental filtration system since there would be large a reduction of VOCs to be treated. This cost analysis will assume that the UV curable coating system will eliminate the need to spray materials containing Oxsol® and acetone in separate booths since the UV curable material does not contain acetone. Thus, UV curable equipment will be available in all booths for the purposes of cost planning in this report.

There are also potential reductions in operating and capital costs due to the time required to apply the coating. The baseline coating is applied at 2-3 mils per pass. The full application time of the baseline coating is approximately 22 hours with a required 5-day cure time prior to overcoat. The UV curable coating system can be applied at roughly 20 mils per pass, 10 times greater then the baseline coating. Also, the UV curable coating cures during the application process, therefore reducing the overall spray and cure time needed to apply this coating to an estimated 13 hours. Based on this initial evaluation of the UV cure application and cure times required, there is an estimated 90% savings in total application and cure time as compared to the baseline process. This potential reduction in cycle time manifests itself as a potential reduction of labor and energy costs as well as a potential reduction in the number of booths required, which also could further reduce both operating costs and capital costs. For this cost analysis, estimates are used for labor and energy costs. All cost estimates are for planning purposes only.

Currently the Northrop Grumman facility is planning to build and install multiple robotic spray booths. This will be done in phases, with one cell (two spray booths) being installed at each phase. The cost associated with a cell is much greater than that of a single booth; therefore, the capital and maintenance cost of each booth depends on whether one or two booths are being installed. Installation of a single booth cell is less expensive than that of a double booth cell, but the ratio of costs is not 1:2.

Estimates of the annual recurring operational costs delta of the UV curable coating from the baseline systems are shown in Table 3. All cost and rates are estimates and are used for planning purposes only. All cost figures are based on the cost to the performing company. All estimated cost values are based on calendar year 2007 dollars.

Table 3. Estimated Delta Annual Operational Cost of the UV Curable Coating from the Baseline.

Estimated Annual Usage for the Delta Cost of UV Curable Coating from Baseline Operation	
	Annual Estimated Delta of UV Curable Coating from Baseline
Material usage	$2,193,000
Utility usage	
Electricity	$62,000
Environmental costs	
Hazardous waste disposal fee	$4,208
Hardware and filters	$50,000
Other operation costs	
Labor hours	$2,754,000
Paint booth maintenance	$100,000
Total	**$5,163,208**

The following assumptions were used in evaluating the potential annual usage and costs of the two coating operations:

- All cost values are based calendar year 2007 dollars.
- All cost figures are based on cost to performing company.
- Aircraft production is assumed to be 255 planes annually.
- Estimated costs of gloves, safety glasses, and bunny suit consumption for the UV curable and baseline process are assumed to be equivalent.
- Environmental, operation, utility, and maintenance costs for the baseline and the UV curable processes are estimated as $5.50/gal of hazardous waste disposal.
- One gal of UV curable material sprays to the same thickness as approximately 2.5 gal of baseline material due to the absence of solvents. Material cost is based on estimated rough order of magnitude cost from the respective suppliers.
- An estimated 3 gal of the baseline material is flushed out due to premature curing in spray gun. This is considered in material usage and hazardous waste disposal fees.
- The baseline process is estimated to require one additional booth as compared to the UV curable material process. Booth savings is based on reduction in cycle time with the UV curable material application.
- Hardware and filter replacement costs are estimated at approximately $50,000 per year per booth.
- Electricity cost is estimated at $62,000 per spray booth per year.

- Actual labor rates are Northrop Grumman proprietary; therefore, a notional $200/hr will be used for this cost analysis.
- The space occupied by parts during heat curing, sanding, and parking is less for the UV curable system, but the associated costs cannot be estimated.

5.3 COST COMPARISON

The cost basis information was used to compare the baseline inlet duct coating system with the UV curable inlet duct coating system. The estimated cost difference between the baseline system and the proposed UV curable system is provided in Table 4. All cost and rates are estimates and are used for planning purposes only. All cost figures are based on the cost to the performing company. All estimated cost values are based on calendar year 2007 dollars.

Table 4. Estimated Delta Cost of Process Costs.

	Delta UV Curable Cost from Baseline
Initial Investment	**-$9,832,000**
Equipment design	-$2,367,000
Robotic spray system purchase	-$6,820,000
UV lamp purchase	-$90,000
Equipment integration	-$3,455,000
Spray booth construction	$3,100,000
Demonstration and Validation	-$200,000
Annual Operating Cost	**$13,263,208**
Material usage	$2,193,000
Utilities	$62,000
Environmental compliance	$54,208
Maintenance and labor	$10,954,000

The following assumptions were used in comparing the process costs of the two coating systems:

- All cost values are based on calendar year 2007 dollars.
- All cost figures are based on cost to performing company.
- The equipment design costs, material formulation, and demonstration and validation estimated costs for the baseline process would not require any additional cost because the process is already established.
- Estimated design cost for the UV curable process is estimated at 30 ± 20% of total equipment purchase costs.
- Equipment integration estimated costs for both processes are estimated at 50 ± 30% of total equipment purchase costs.
- The annual operating costs of both coating systems are based on the data presented in Table 3.
- UV curable demonstration and validation costs are actual costs.

- Costs for the robotic spray systems and UV lamps for the UV curable process are estimated based on costs incurred during the demonstration and validation.
- Costs for the baseline robotic spray system are actual costs.

Table 4 shows a potential significant reduction in operating costs of the UV curable coating system. The infinite pot life of the UV curable system has the potential to eliminate the need to flush out the gun every 15 applications, which would reduce hazardous waste disposal and material usage. The absence of solvents in the UV curable system further has the potential to reduce the material usage as well as the frequency with which the hardware and filters must be changed. The estimated reduction in cure time of the UV curable system has the potential to reduce the cycle time, which in turn reduces labor, energy, and paint booth usage. Several other cost benefits that cannot be quantified here are expected to result from the implementation of the UV curable coating system.

5.3.1 Life-Cycle Cost Analysis

A life-cycle cost analysis was performed using the data from Table 4. The objective of this analysis is to determine the potential for the UV curable coating system as an economically viable alternative to the baseline coating system. The life-cycle cost evaluation was calculated by totaling the estimated initial investment required as well as the estimated annual recurring costs over the expected 15-year life of the equipment. Per ECAM guidance, this approach performs the following:

- Estimates the annual cash flows using the cost data described above
- Discounts future cash flows for the time value of money
- Calculates financial performance measures (net present value[NPV] and internal rate or return)
- Compares these measures with acceptance criteria.

A summary of the estimated delta life-cycle cost savings associated with the UV curable coating system is provided in Table 5.

Table 5. Estimated Life-Cycle Cost Analysis.

Coating System	Delta Installation Cost	Delta Annual Operating Cost	Delta Life-Cycle Cost
Delta UV curable cost from baseline	-$9,832,000	$13,263,208	$189,116,120

Three performance measures for investment opportunities were then considered in the ECAM evaluation: payback period, NPV, and internal rate of return (IRR). The payback period is the time period required to recover all the capital investment with future cost avoidance. NPV takes this investment-return analysis one step further by calculating the difference between capital investments of the two coating systems and the present value of future annual cost benefits associated with the UV curable coating system. This value represents the life-cycle cost associated with the UV curable coating system. The IRR is the discount rate at which NPV is equal to zero.

NPV and IRR account for the time value of money and discount the future capital investments or annual cost benefits to the current year. For NPV and IRR, a 4% discount rate and a 15-year life-cycle period was used for this financial evaluation. The 15-year estimated net present value, estimated internal rate of return, and estimated discounted payback period for the UV curable system are shown in Table 6. Table 7 summarizes the investment criteria used to determine whether the UV curable system is a financially viable alternative to the baseline coating system.

Table 6. NPV, IRR, and Discounted Payback Period for the UV Curable Coating System.

NPV	IRR	Discounted Payback Period
$137,633,485	134.90%	0.74 years

Table 7. Summary of Investment Criteria.

Criteria	Conclusions
NPV > 0	Investment return acceptable
NPV < 0	Investment return not acceptable
IRR > discount rate	Project return acceptable
IRR < discount rate	Project return not acceptable

The estimated NPV value for the UV curable coating system is positive, and the estimated IRR is greater than the discount rate, which, based on the investment criteria in Table 7, means that implementation of the UV curable coating system is potentially an economically viable alternative to the baseline coating process. Therefore the UV curable coating system has the potential to provide a higher value to the facility than the baseline coating system.

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6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

The robotic application equipment and cure equipment were designed and developed under an effort summarized in Appendix A of the Final Report. This funding was utilized to support and facilitate the transition of the technology to a weapon system.

The UV curable material costs more per gallon of material; however, the overall quantity of the UV curable material is less than the baseline material. The baseline material contains VOCs and exempt solvents, which flash off after applications. However, with the UV curable system, there are no VOCs and no solvents; therefore, the wet film thickness of the material is equivalent to the dry film thickness of the material, thus reducing material volume loss.

The largest cost associated with this project is the capital cost for a robotic spray booth facility and the associated environmental equipment. Since the cost evaluation of implanting the spray booths is so complex and has multiple variables as well as multiple configurations and options, this is the area where the cost evaluation can have the greatest fluctuations. A thorough cost analysis and spray booth design is needed to fully capture the true cost of implementation.

6.2 PERFORMANCE OBSERVATIONS

The test results are summarized in Table 1. Overall, the material meets most of the material requirements. This demonstrates that the material has potential as a viable replacement for the baseline material. The material adhesion following fluid exposures to MIL-DTL-83133 (JP-8) and MIL-PRF-85570 Type II (alkaline cleaner) showed some deviation from the material requirements. The test coupons exposed to the alkaline cleaner were tested and resulted in tensile strength that deviated less than 10% from the goal. This deviation in performance may be due to the test method used for these specific test coupons. The test method defines a test speed of 0.1 in/min; however, these coupons were tested one order of magnitude lower at 0.01 in/min due to an error by the lab technician. Since the adhesion testing of the UV curable material following these exposures were within 10% of the requirement, it is likely that the testing of the material at the correct test speed would yield results that meet the material requirements. The UV cured material will be retested under alternate funding to establish the material adhesion following exposure to MIL-PRF-85570.

Following exposure to JP-8 the material failed the flatwise tensile test. These coupons were tested with the same method as described in the paragraph above. This discrepancy in test method may account for some of the loss of adhesion; however, the test method is not the only factor affecting the material's adhesion following fluid exposure. Additional testing will be performed on test coupons following MIL-DLT-83133 exposure, and this issue will be addressed in an effort summarized in Appendix A of the Final Report.

The compatibility of the material with the baseline material was also an area where the UV curable material did not meet the full requirement. Again, flatwise tensile strength was used as the test method to demonstrate material compatibility to the baseline material. The same discrepancy in test speed was repeated in this testing. Also, the results showed partial adhesive failures to the pull member bonded onto the UV curable material for test. This shows failure of the surface preparation to the test coupon, which does not represent the platform application. These two factors are potentially large factors that would affect the tensile strength results from the testing. These test configurations will be retested under alternate funding to establish the UV repair material adhesion.

Once the adhesion properties can be verified, the UV curable material could be used as a viable alternative to the baseline coating and repair material. The UV curable coating provides significant benefits in reductions of cycle time, VOC and HAP emissions, and overall cost.

6.3 SCALE-UP

Robotic application is dependent on development of a cure system for this type of large-scale application. Without development of the application and cure equipment, this process is not a viable technology for transition for this specific application. This robotic application, UV lamp and material scale-up issue are being addressed in an effort summarized in Appendix A of the Final Report to develop the equipment.

6.4 OTHER SIGNIFICANT OBSERVATIONS

UV curable materials can provide great benefits to the original equipment manufacturer (OEM) and depots, but the equipment is the key factor in the implementation of the technology. Without adequate cure equipment, the UV technology cannot be used for repair or for OEM application. Along with the development of UV cure equipment is the safety and UV exposure concerns that need to be addressed with the implementation of the UV technology. Since this is a new technology for the aerospace industry, many hurdles from those who are not aware of the UV technology will have to be overcome for implementation. With time and a more widespread understanding and knowledge of the technology, UV could be part of the future of the aerospace industry.

6.5 LESSONS LEARNED

This demonstration of the UV curable coating was a successful demonstration of UV curable technology for aerospace application. Prior to this demonstration, UV cure technology has not been used for aerospace application. This demonstration was useful in proving that UV curable technology could be a viable technology aerospace application, as long as the correct application is chosen.

One key in the successful demonstration is the coordination and attendance of the end users and key government personnel for the demonstration. Without the participation of both the end users and the government personnel, many ideas and potential technical concerns would not have been addressed during this demonstration.

6.6 END-USER/ORIGINAL EQUIPMENT MANUFACTURER (OEM) ISSUES

End users include Northrop Grumman, Lockheed Martin, and Boeing. The optimization/baseline testing as well as the demonstration/validation will address a number of potential concerns:

- Ability of the UV cured material to meet the baseline platform requirements
- Potential manufacturing cycle time reduction
- Ability to spray apply and cure a UV coating
- Performance impact of the repair UV curable coating on the baseline material
- Validate that the material can be spray-applied and cured in order to demonstrate compatibility with baseline materials
- Demonstrate that the filled material is appropriate for field use by showing that the material can be used to repair the current baseline material while maintaining the overall aerospace performance characteristics
- Time and labor needed to implement this method and identify if there is any interference with present methods and schedules
- Cost-benefit analysis (primarily labor for application process, equipment, reduction in amount of material usage, and VOC emissions)
- Safety concerns about UV exposure during cure.

The equipment to be used for testing is a custom built prototype that will be developed by Pratt Whitney Automation for the robotic application, and a commercial off-the-shelf UV curing system built by Fusion UV.

The robotic application system will be tailored to specifically apply the material being tested to the parameters determined during the material development phase of this effort. The design and fabrication of the integrated system will be performed under the effort summarized in Appendix A of the Final Report.

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7.0 REFERENCES

Demonstration/Validation Plan of WP-0408, www.estcp.org.

ESTCP Project WP-0303, www.estcp.org.

SERDP Project WP-1181, www.serdp.org.

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APPENDIX A

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